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## Adjustment of a high pressure die casting simulation model against experimental data

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### Abstract

In addition to the typical difficulties associated with the numerical simulation of metal casting processes, the special characteristics of the high pressure die casting (HPDC) increase the difficulty of obtaining reliable results.

The process followed to define and adjust one HPDC simulation model against experimental measurements by means of inverse modelling, is presented together with information related with the test campaign. This knowledge may be of interest for other researchers interested in the HPDC simulation and/or in the simulation models adjustment.

The case of study corresponds to the specific case of one variation of the alloy AlSi9Cu3 (in-house developed) and one variation of the H13 steel (in-house developed), used for the mold manufacturing. The simulation models include the mold thermal evolution during the consecutive cycles of the manufacturing process, together with the cavity filling and the later cooling of the alloy.

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### 1. Introduction

The obtaining of reliable simulations of metal casting processes is not a trivial task. The results do not only depend on numerical codes in which they are based. The use of the appropriate values for the model parameters is essential to avoid results poor or even erroneous.

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The obtaining of material properties for the whole range of temperatures involved in the metal casting processes is always difficult. Additionally, the determination of the values of some boundary conditions, as for example the heat transfer coefficients (HTC), is even more complex. The typical solution consists in the utilization of values extracted from literature but they usually correspond to standard values and not always provide satisfactory results.

In the particular case of the HPDC (high pressure die casting) these difficulties augment. The complexity of the molds (fixed and movable plates, cores, cooling channels, etc.) and the machine parameters (injection temperature, piston velocities, cycle times, etc.) increase the number of boundary conditions to be included in the modelling. Moreover, it is a continuous manufacturing process based on consecutive cycles where the alloy fills the mold cavity at very high velocities followed by fast cooling rates. These characteristics added to the intricate geometries and small thicknesses typical in this type of manufactured parts increase importantly the numerical complexity of the calculations.

All these difficulties reveal the challenge of obtaining accurate HPDC simulation models and the interest of their adjustment to reproduce the real process as much as possible.

## 2. Methodology

The correct definition of the simulation model requires the assignment of the appropriate values to the material properties and boundary conditions. The limitations of bibliography data and the extreme difficulty of the direct determination of these values have inspired the application of inverse methods to avoid these difficulties. As Dantzig and Rappaz explains at reference [1], the inverse methods are a subset of the field of numerical optimization where the objective is to minimize the difference between the experimental measurements and the simulation results. In the case of metal casting simulation, these measurements are temperatures registered at determined points during experimental tests. The methodology consists basically in an iterative process where several parameters of the model are modified until the temperatures predicted by the simulation are in agreement with the experimental measurements, reaching the desired correlation level. This iterative process may be executed manual or automatically by means of optimization algorithms. The main advantage of the automatized methods is the cost and time reduction but they do not always succeed. Sometimes the correlation level achieved is not good and sometimes the values of the adjusted parameters have no physical sense. In the case of the manual adjustment, each step of the iterative process must be performed manually by the researcher but it allows a better control of the parameter modifications and generally provides more robust adjustments.

Different authors have applied inverse methods to adjust the values of different parameters involved in the metal casting simulation. Most of them are focused on the determination of the HTC between the mold and the alloy, as in the case of references [2,3] for metallic molds and [4–7] for ceramic shell molds. Other works have dealt with the determination of both, the boundary conditions and material properties, but its number is more reduced. Some examples are the case of reference [8] focused on direct chill casting or references [9–11] focused on investment casting. The HPDC process is tackled in reference [12] but only the heat transfer coefficient between the alloy and the mold is determined and the experimental values are limited to mold temperatures.

The work presented here corresponds to the adjustment of a finite element model that simulates the whole HPDC manufacturing process, that is, the mold heating during the pre-heating cycles, the cavity filling and the part cooling. Not only the HTC but also the rest of boundary conditions and the material properties have been adjusted based on temperatures experimentally measured at mold and alloy. The case of study corresponds to the specific case of one variation (in-house development) of the AlSi9Cu3 alloy (referred as AlSi9Cu3 hereafter) and one variation (in-house development) of the H13 steel (referred as H13 hereafter) used for the mold manufacturing. The iterative process of adjustment has been performed mostly by means of manual procedures.

Due to the iterative nature of the methodology, the number of simulations that is needed perform is very high. So, it is highly advisable the use of models as simple as possible, in order to reduce the calculation times. For this reason, the adjustment has been performed in two different phases. During the first phase, the material properties of the involved materials (alloy and mold) have been adjusted based on a gravity metal casting prototype. The major simplicity of this manufacturing process makes easier the model adjustment. In the second phase the boundary conditions and the heat transfer coefficients involved in the HPDC process have been adjusted based on a HPDC prototype. The material properties previously obtained, have been used.

### 3. Design of tests and implementation

The AlSi9Cu3 alloy, whose range of chemical composition is collected in Table 1, is widely used in aluminum die casting. The main reasons are its good castability, improved by the silicon content, combined with a medium strength, enhanced by the copper, maintaining a good machinability. The H13 steel for its part is very used in manufacturing of die casting molds. It is a tool steel with excellent wear resistance and good thermal shock resistance, whose chemical composition is shown in Table 2.

Table 1. Chemical composition % of AlSi9Cu3

Si	Cu	Mn	Mg	Fe	Ni	Pb	Sn	Ti	Zn	Al
8.0-11.0	2.0-3.5	0.1-0.5	0.1-0.5	Max 0.80	Max 0.3	Max 0.2	Max 0.1	Max 0.15	Max 1.2	Rest

Table 2. Chemical composition % of H13 steel

C	Cr	Mo	Si	V	Fe
0.32–0.40	5.13–5.25	1.33–1.4	1.0	1.0	≥90.95

The gravity prototype corresponds to a simple cylindrical geometry (part Ø40mm 200mm length and 30mm mold wall) shown in Fig. 1 left. Thermocouples K type have been used to register the temperature into the cast part and also into the mold wall.

Following the same philosophy of using simple cases, a HPDC prototype has been designed and manufactured to avoid dealing with the usual complexity of HPDC molds. The geometry of the cavity corresponds to a cylindrical shape (Ø50mm and 250mm length). This shape has been completed with a simple die gating system composed by the runner, several gates and a pair of overflows (see Fig. 1 right). The mold includes also one ejecting mechanism and one cooling channel. The cross section of the injected part is thicker than the typical values used in HPDC, but it allows to measure the temperature inside the part during the manufacturing process. A thermography camera has been used to record the temperature distribution at the interface between the fixed and movable plates of the mold. It makes possible to obtain the temperature distribution along the whole surface but only during periods in which the mold is open. The alloy temperature has been measured by an encapsulated thermocouple K type inserted into the mold cavity. This method allows to register the alloy temperature during the whole period since the injection until the part ejection. It provides also less variability in the measurements of different trials because the thermal behavior inside the part is more stable than near surface. Anyway the temperature in the part surface has been also registered by the thermography camera during the mold opening. The main disadvantage is that the thermocouple remains inserted in the manufactured part and is broken during the part ejection. So, for each trial a new thermocouple must be placed to perform the measurements. The mold has been manufactured with one specific system that makes possible to place the new thermocouple in a way relatively easy and fast and assuring always the same position.

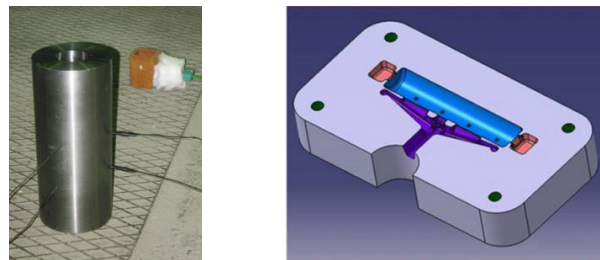


Fig. 1. Instrumented gravity mold prototype (left). Movable plate of the HPDC mold prototype (right)

A series of castings of the gravity prototype have been performed in controlled conditions. The cooling curves obtained are shown in Fig. 2, where the curves that reach higher temperatures (above 600°C) correspond to the alloy

and the rest to the mold (values below 200°C). These measurements have been pre-processed and the average curves of the alloy and mold have been calculated to be used later during the model adjustment.

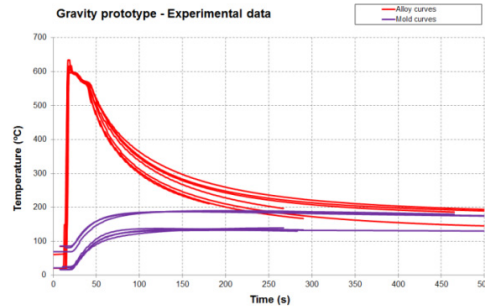


Fig. 2. Experimental curves for the gravity prototype

It is a well-known fact that at the beginning of the HPDC process the mold is too cold and it needs to be heated. The parts initially manufactured will be faulty until the mold reach the thermal stabilization. Notice that this thermal stabilization does not mean uniform or constant temperature, the temperature distribution is not uniform along the mold and also varies during the manufacturing cycle. This fact has been taken into account during the experimental trials and several parts have been manufactured to reach the mold thermal stabilization prior to collect the temperature measurements.

The high velocities reached in the HPDC process, not only for the alloy injection but also in the alloy cooling, have been one of the main challenges tackled during the experimental phase. On one side, it has not been possible to register alloy temperatures above 592°C although different attempts have been performed increasing the alloy temperature at furnace, reducing the cycle time to increase the mold temperature or increasing the data registering frequency (until 1000 Hz). Other authors, who have also found this type of difficulties, see reference [13], think that the reason may be that the alloy fills the mold partially solidified due to the cooling suffered in the plunger and gating system. On the other side, the cooling shown by the temperature curves is so fast that is not possible to detect the typical slope change associated with the solidification range. The Fig. 3 left, shows the alloy cooling curves registered during the tests once synchronized. As can be observed there is a first period of time where the temperature is between 100°C and 200°C, which corresponds to the measurements performed by the thermocouple once located into the mold but before the alloy injection. That is, these temperatures correspond to the air into the mold. Next, can be observed a drop in the temperature, which corresponds to the mold open/close to initialize the machine cycle. Finally there is a fast increment of temperature corresponding to the alloy arrival, followed by the alloy cooling. The cooling of the part has been artificially prolonged into the mold to get more data, because in the moment that the part is ejected breaks the thermocouple and the measurements stops. The temperature distribution along the mold has been registered by means of the thermography camera. The Fig. 3 right, shows an example of the temperature distribution along the mold registered during the manufacturing process.

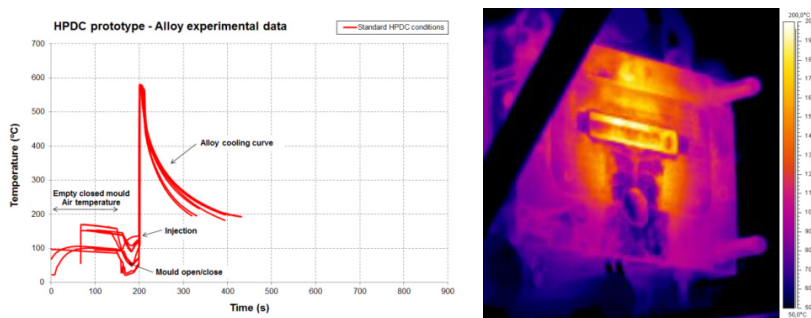


Fig. 3. Typical temperatures registered inside the injected part (left) and in the mold (right)

The temperature measurements of the alloy and the mold have been pre-processed separately and later synchronized. Finally, two temperature curves representative of the process have been defined. The first curve is shown in Fig. 4 left, and corresponds to the average temperature at areas near the cavity of the mold fixed plate during the standard manufacturing cycles. With the thermography camera is only possible to measure these temperatures during periods when the mold is open, so the temperatures expressed in dotted line do not correspond to measured values. The only one interest of these dummy values is to represent the cycle times when the mold is closed. The second curve corresponds to the case when the test part is manufactured. The Fig. 4 right shows, the average temperature of the mold fixed plate synchronized with the average alloy curve. The manufacturing times differs from the standard cycle times due to the time needed to place the thermocouple. Apart from that, in this case the part ejection has been delayed.

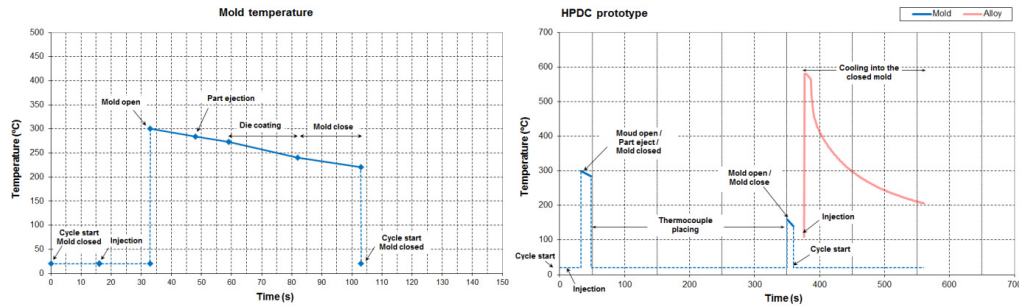


Fig. 4. Representative temperature of the mold for standard cycles (left). Synchronized temperatures of the mold and alloy (right).

#### 4. Adjustment of the simulation model

##### 4.1. First phase – Adjustment of the material properties, based on the gravity prototype

The initial model corresponds to our best approximation to the problem based on the experimental pouring temperature, the values extracted from bibliography and the previous experience of the involved researchers. In spite of it, the obtained results are not good enough, see Fig. 5 left. The cooling curves obtained from the simulation (dotted lines) do not match with the registered during experimental tests (solid lines). This fact reveals the necessity of the model adjustment in order to get simulation results more adjusted with the real behavior of the process.

The variables subjected to modification during the adjustment are the material properties of the alloy and the mold (thermal conductivity, specific heat, density and in the alloy case the solid fraction curve), the HTC between them, and the convection coefficient with the ambient. Temperatures of pouring and ambient are assumed fixed. The temperatures registered experimentally, are the reference values to evaluate the adjustment. After numerous iterations, has been achieved a simulation model whose results agree with the temperatures registered experimentally (see Fig. 5 right).

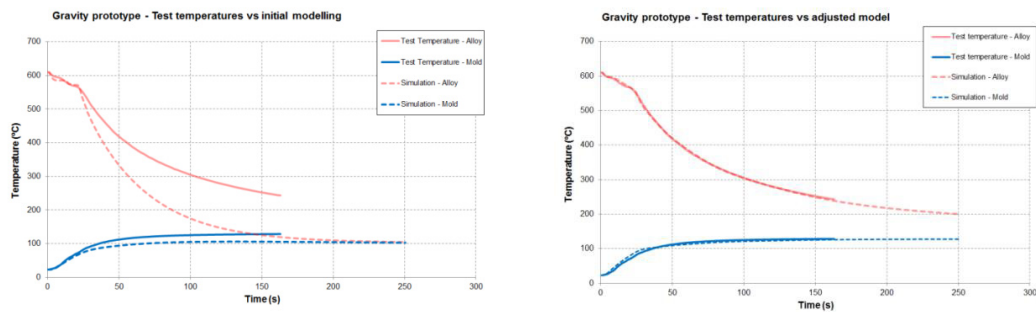


Fig. 5. Experimental data vs simulation results. Initial model (left) and adjusted model (right)

#### 4.2. Second phase – Adjustment of the HPDC model

The material properties obtained in the model adjustment of the gravity prototype have been directly included in the HPDC simulation model. The cycle times and the furnace temperature registered during the experimental tests have been assumed also as fixed values. So in this model the variables subjected to modifications are limited to the boundary conditions (injection temperature and cooling conditions) and to the HTC related with the HPDC process (between the alloy and mold and between the mold plates).

A 3D detailed model representative of the whole geometry of the mold has been developed. In this case the term “whole geometry” is referred to the central areas of the plates where the cavity is located (typically interchangeable area) and not the whole mold plates. Fig. 6 shows part of the finite element meshes used in the models.

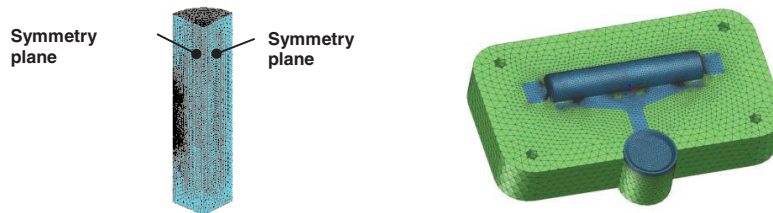


Fig. 6. Mesh of the gravity prototype (left) and of part of the HPDC prototype mesh (right)

The initial model based on this 3D detailed mesh has been developed with our best approximation to the problem. Applying the material properties previously fixed and taking into account the registered data during the test campaign (the furnace temperature and cycle times), the bibliography data and the previous experience of the research team. Nevertheless, as can be observed in Fig. 7, the cooling curves obtained as simulation results (dotted lines) do not match as good as it is desirable with the temperatures registered during test campaign (solid lines). It is reminded that dotted curves at ambient temperature represent dummy values and no real temperatures.

The iterative nature of the adjustment methodology makes the calculation times a critical aspect. The numerical complexity of the HPDC simulation is high, even in cases where the part geometry is simple. Moreover it does not only require the simulation of the alloy injection process, it is also needed simulate previously several manufacturing cycles to obtain the temperature distribution in the mold. All of that increases importantly the calculation time needed, making much more complex the obtaining of the adjustment of the HPDC simulation model. In order to reduce as possible the calculation times, the first approximations have been performed based on a simplified model. This simplified model, which can be assumed as a pseudo-2D model, corresponds to a slice of the detailed model where only heat transfer has been considered. More information about the model simplification used can be found in [14]. Although the model is not fully representative of the real case, its use has made possible a more agile preliminary approximation to the problem and a faster advance in the adjustment process.

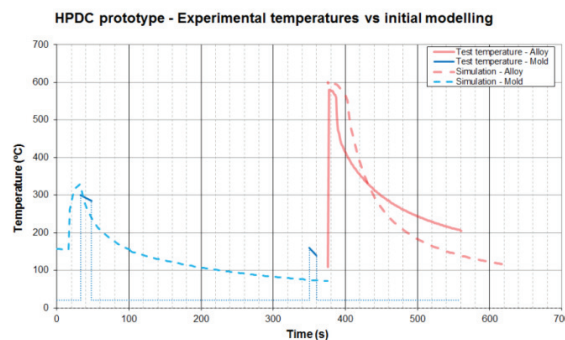


Fig. 7. Experimental measurements vs simulation results. Initial model



## 5. Results and discussion

The adjustment of the model has required the inclusion of the whole process followed during the experimental tests. That is, it has been needed to include the simulation of several cycles until reaching the mold thermal stabilization, the cooling suffered by the mold during the thermocouple location, the injection process and the later cooling of the injected part. Finally after numerous iterations, has been obtained a set of two simulation models whose results agree with the experimental temperatures measured during the test campaign. This set of two models is formed by the model corresponding to the cycles calculation (which must be executed first) and the model representative of the injection process (which must be executed considering as initial conditions the thermal distribution obtained from the cycles calculation).

Fig. 8 shows the results obtained from the simulation model (dotted lines) compared with the temperatures measured during the test campaign (solid lines). As can be observed the obtained results match good with the experimental measurements. The average temperature registered at mold during test (about 300°C) is into the temperature range obtained from simulation. The cooling curve of the alloy obtained from simulation presents a curvature very similar to the curve measured experimentally, although in the simulation case is slightly displaced in time. At temperatures above 585°C is not possible to compare the temperature results as it has not been possible to measure experimental temperatures above this value.

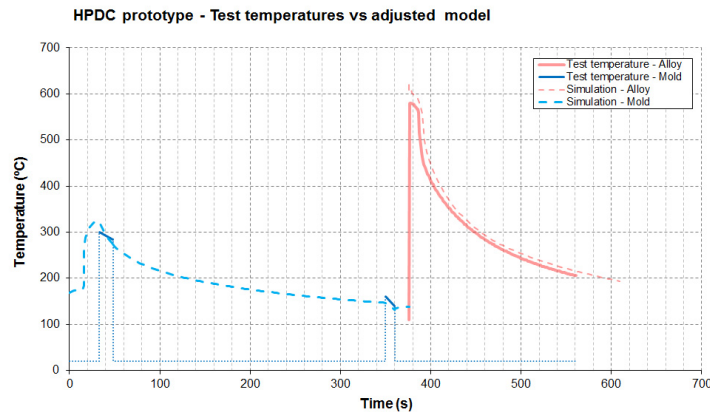


Fig. 8. Experimental measurements vs simulation results. Adjusted model

## 6. Conclusions

One set of two simulation models adjusted to the high pressure die metal casting process (HPDC) for the specific case of one variation of the AlSi9Cu3 alloy and one mold manufactured on one variation of steel H13, have been obtained. One of the simulation models is focused on the cycles calculation and the other on the injection process. The simulation models include the geometry of the manufactured part and also the geometry of the mold. The set of models is representative of the whole manufacturing process, since the cycles to reach the mold thermal stabilization, until the manufactured part ejection including the injection process. The simulation is a transient analysis that combines the fluid dynamics with the heat transfer analysis, including the heat latent release due to solidification.

The improvement reached in the models accuracy, that is, the agreement between simulation results and experimental measurements, is very significant as can be observed in Table 3. Although the studied geometries are quite simple, these adjusted models may be directly moved to the case of industrial parts by substituting the prototype geometries by the real ones and adapting the values of the cycle timing. Preliminary results obtained for industrial geometries based on the values adjusted in this work have provided promising results.

Table 3. Comparison between the error\* in the initial model and in the adjusted model (\* Error = 100 x (|Temperature predicted – Temperature measured|) / Temperature measured)

Models	Gravity case Alloy	Gravity case Mold	HPDC case Alloy	HPDC case Mold
Initial model	30.9 %	14.6 %	20.3 %	31.5 %
Adjusted model	0.5 %	4.5 %	4.8 %	6.1 %

Although other papers based on the application of inverse methods to metal casting simulation exist, most of them are focused in the adjustments of a short number of parameters (typically the heat transfer coefficient) or in other metal casting processes. The main contribution of this work consist in confirming the applicability of this adjustment methodology to the simulation of a process as complex as the high pressure die casting. Apart from that, the paper details the different steps and difficulties found, which may be of interest for other researchers interested in HPDC simulation or in this type of adjustment methodology.

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